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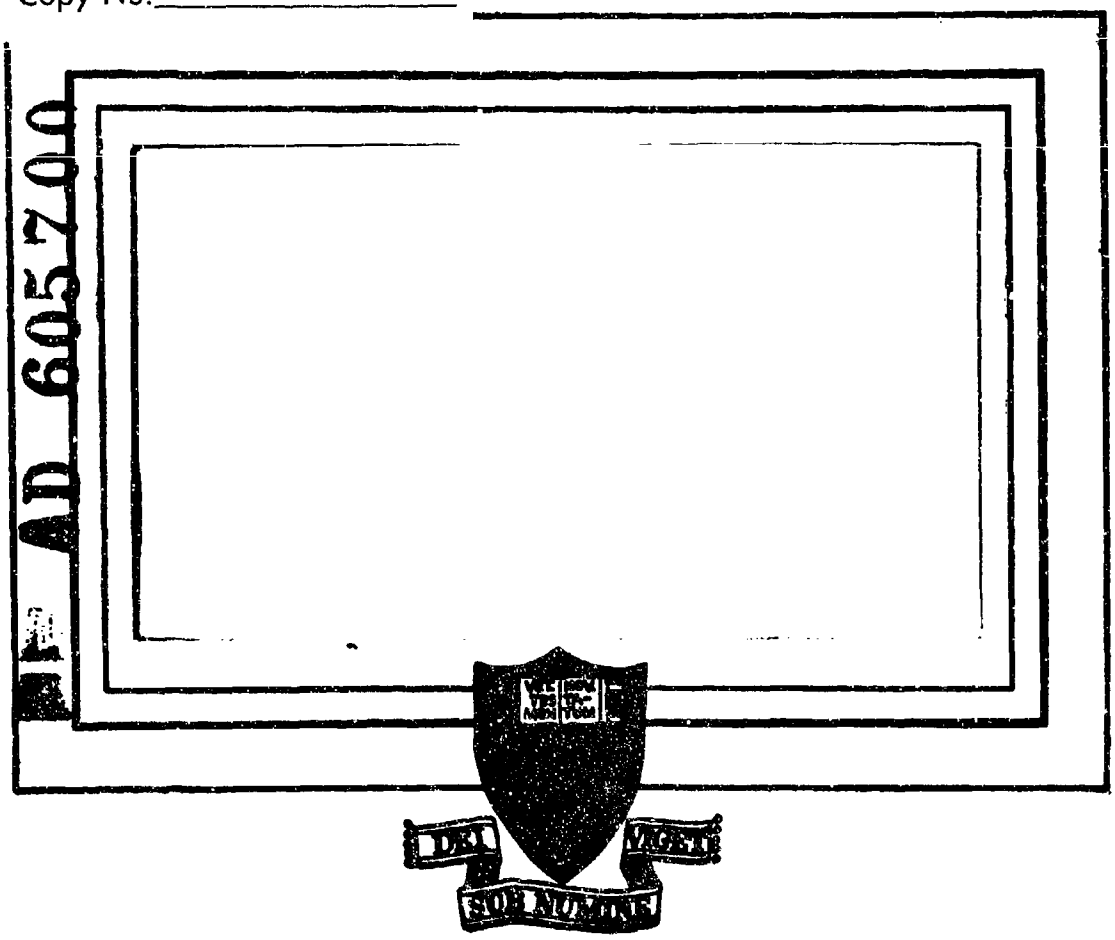

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SOME RESEARCH PROBLEMS IN THE STEADY-STATE BURNING OF COMPOSITE SOLID PROPELLANTS

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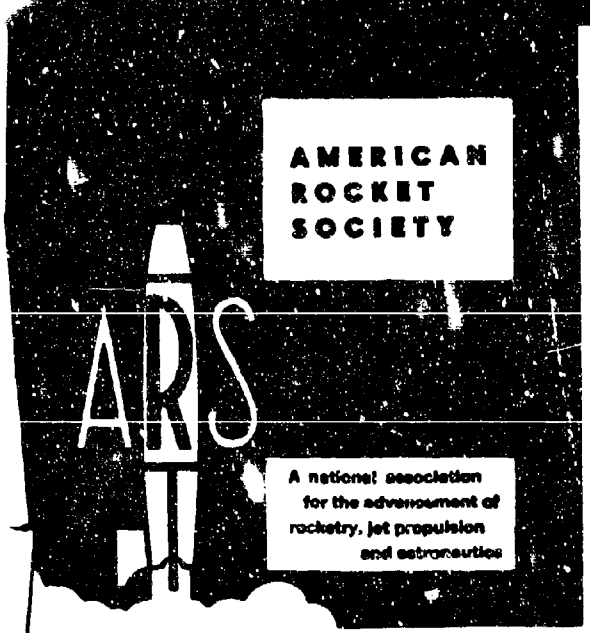
Princeton, New Jersey



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SOME RESEARCH PROBLEMS IN THE STEADY-STATE BURNING OF COMPOSITE SOLID PROPELLANTS

by

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Presented at the Solid Propellant Rocket Research Conference, Princeton University, Princeton, New Jersey, January 28-29, 1960.

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This was derived for composite propellants of the ammonium perchlorate type on the basis of a physical model of the reaction zone called the "granular diffusion flame." The parameter a, called the gas-phase reaction time parameter, was defined as follows:

$$a \cong \frac{\rho_s R T_g}{\bar{M}_g} \cdot \frac{[C_g(T_g - T_o) - Q_s]^{1/2} / [\lambda_g (T_l - T_g)]^{1/2}}{A \exp(-E/RT_g)} \qquad (2)$$

in which the Arrhenius function in the denominator pertains to the gas phase oxidation reaction, T_o, T_s, T_g, T_l are temperatures respectively at ambient conditions, at the surface, at the effective region of the gas phase reaction, and at the hot end of the flame zone. The name "reaction time parameter" indicates that it varies inversely as the chemical reaction rate in the gas phase, although the dimensions of a do not correspond to time.

The parameter b, called the "diffusion time parameter" was defined as follows:

$$b \cong \mu^{1/3} \rho_s \left(\frac{RT_g}{\bar{M}_g}\right)^{5/6} \cdot \frac{[C_g(T_g - T_o) - Q_s]^{1/2} / [\lambda_g (T_l - T_g)]^{1/2}}{(P_1 D_{g1})^{1/2}} \qquad (3)$$

where the gaseous diffusivity D_{g1} is an average value for the diffusion flame, taken at one atmosphere pressure, and P_1 is one standard atmosphere in proper units. The average mass content of the tiny pockets of fuel vapor generated at the heterogeneous propellant surface is denoted by μ. The name "diffusion time parameter" indicates that it varies inversely as the diffusivity of gases in the reaction zone, although the dimensions of b do not correspond to time.

It was found experimentally (Ref. 1, 3, 4) that Eq. (1) fits the r - p data for a variety of simple propellant formulations based on Rohm and Haas P-13 polystyrene copolymer resin as fuel and ground ammonium perchlorate as an oxidizer. To test the fit sensitively, it was necessary to make burning rate measurement over a wide pressure range, from sub-atmospheric pressures to about 100 atm. Data obtained from other sources by private communication indicated reasonable agreement with the theoretical law, but generally the measurements were not taken below about 20 atm. pressure. Some serious departures were found in some data from other sources, for which there has been no explanation as yet.

In an effort to test this burning rate theory more decisively, and in order to examine the further implications of the particular granular diffusion flame model, a series of questions has been set up as a basis for the present research program:

1. How reliable are the burning rates measured in a conventional strand burner, and how do these rates compare with rocket motor determinations of burning rate?

2. How is the b parameter related to average oxidizer particle size or the particle size distribution?

3. The theoretical law was based on the hypothesis that the principal mode of energy transfer from the hot flame to the surface is by molecular gas conduction, and that radiant transfer in particular is negligible. Can this be verified by direct radiant energy measurements?

SOME RESEARCH PROBLEMS IN THE STEADY-STATE BURNING OF COMPOSITE SOLID PROPELLANTS[1]

by

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ABSTRACT

This paper outlines a number of basic problems in the theory of steady-state combustion of solid propellants, particularly of the ammonium perchlorate composite type. It represents an extension of the earlier research at Princeton that led to a theoretical burning rate law for composite propellants that was based on the concept of granular diffusion flame. This paper is in the nature of a progress report in which, although no final conclusions are drawn, the new experimental approaches are described, and some puzzling difficulties are analyzed. Specifically, the experiments deal with three topics: refinement of methods for measuring burning rate; the role of radiative energy transfer in the burning process; and the connection between oxidizer particle size and the b parameter in the above-mentioned theoretical burning rate law.

A. Introduction

The general objective of the researches on steady-state burning that are underway in the Princeton laboratory is to determine critically the validity of the theoretical burning rate law presented in Ref. 1 in 1958:

$$\frac{1}{r} = \frac{a}{p} + \frac{b}{p^{1/3}} \qquad (1)$$

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1. This research is supported by the Office of Naval Research, in part by funds provided by the Advanced Research Projects Agency, Contract No. ONR 1858(32), and in part through Project Squid, Contract No. Nonr 1858(25) NR-098-038.

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It was found experimentally (Ref. 1, 3, 4) that Eq. (i) fits the r - p data for a variety of simple propellant formulations based on Rohm and Haas P-13 polystyrene copolymer resin as fuel and ground ammonium perchlorate as an oxidizer. To test the fit sensitively, it was necessary to make burning rate measurement over a wide pressure range, from sub-atmospheric pressures to about 100 atm. Data obtained from other sources by private communication indicated reasonable agreement with the theoretical law, but generally the measurements were not taken below about 20 atm. pressure. Some serious departures were found in some data from other sources, for which there has been no explanation as yet.

In an effort to test this burning rate theory more decisively, and in order to examine the further implications of particular granular diffusion flame model, a series of questions has been set up as a basis for the present research program:

1. How reliable are the burning rates measured in a conventional strand burner, and how do these rates compare with rocket motor determinations of burning rate?

2. How is the b parameter related to average oxidizer particle size or the particle size distribution?

3. The theoretical law was based on the hypothesis that the principal mode of energy transfer from the hot flame to the surface is by molecular gas conduction, and that radiant transfer in particular is negligible. Can this be verified by direct radiant energy measurements?

4. How do propellants based on other fuels and oxidizers compare with the theoretical burning rate law, and can deviations be explained in terms of an altered flame model?

5. Can the connection between particle size and granular flame zone structure lead to an interpretation of the effect of particle size on erosive burning?

This paper is a progress report on the first three of these questions. Although final answers are not yet in hand, some of the results are provocative and, we believe, worthy of wider attention. At the same time, some of the experimental methods deserve to be discussed.

B. Study of Techniques of Measurements with a Strand Burner

Burning rate determinations are made in a standard strand burner of the type described in (Ref. 2, 3, 4) and modified to include an upward purge of gas in a chimney surrounding the strand as shown in (Fig. 1, 3) The purge gas flow rate is controlled by a metering valve with micrometer control, which is left at a constant setting for all runs, thereby providing a constant flow velocity in the chimney. Ignition is performed by a wire passing through the top of the strand and burning proceeds counter to the purge gas flow.

Close consideration has been centered on sources of errors in the strand burning rate determinations made with this apparatus so that reliable comparisons may be made both with the theoretical burning rate law and with the burning rates obtained from small motors. Possible systematic errors were investigated with the following results. Purge velocities within the chimney ranging from 0.6 to 2.0 ft per second did not detectably affect the burning rate at 500 psi, which was the standard pressure for running these checks. The usual purge gas is pure N_2, but for radiation determinations which are described later 10% O_2 is added to the purge to burn up the smoke that otherwise obstructs the optical path. Therefore, the effect of O_2 in the purge gas was checked and shown to be well within the statistical scatter up to pure air concentrations. Later work will extend the range of O_2 concentrations. The standard method uses strands with surface inhibition consisting of two coats of Testor's Butyrate Dope (Blue), a model airplane lacquer, plus two coats of 5% Bakelite V.Y.L.F. plastic in methylene chloride. Checks of inhibited versus uninhibited strands at 100 psig showed no significant difference either in rate or in standard deviation of five runs repeated at each condition. This opens the question of the desirability of continuing to use inhibitors for this work, which is still being studied. The effect of strand diameter was investigated with 7/16 inch diameter strands. Compared with the standard 1/4 inch strands at 500 psig, the 7/16 inch strands showed a 3 percent increase in burning rate over the 1/4 inch strands.

The strands are manufactured by being extruded in the uncured liquid state into wax molds from which they are later removed (Fig. 2). In cases where coarse oxidizer particle sizes were used, it was noted that when the curing took place with the molds constantly in one position, a gravity induced settling of oxidizer took place. To avoid this the curing oven was fitted with a rotary mold support driven slowly by a motor to constantly rotate the molds about a horizontal axis during curing. This eliminated the gravity settling. However, checks were run to determine the effect of possible separation of fuel and oxidizer at the mold surfaces. Burning rates were determined for strands cut from a 1 x 5 x 7 inch block of propellant and compared for variations between outside and inside cuts. At 500 psig, the outside cuts gave rates agreeing with standard cast strand data, but the inside cuts gave rates 7 percent lower. This indicated some separation at the surface with the resultant higher oxidizer concentration within the strand giving the excessive rate.

Non-flat burning surfaces may, in some instances, give incorrect burning rates. The flatness of the surface was checked by suddenly water quenching the strands during burning (Fig. 4). The surface positioning was generally satisfactory, with occasional unsatisfactory large tilt possibly caused by off center ignition.

As opposed to the preceding sources of systematic errors, random errors were evaluated. Webb (Ref. 3) gives the random scatter attributed to measurement uncertainties of pressure, timing interval, and initial temperature as approximately ± 0.7 percent at 500 psia, with an additional ± 3 percent uncertainty attributed to non-uniform propellant properties. Taback (Ref. 4) finds that known sources of error can account for 1.5 to 4% scatter over his pressure range, while his experimental scatter is about twice this amount. These results were obtained without the chimney purge system. The percent standard deviation at 500 psig of sets of 5 runs each has for the present system ranged from 1 to 4 percent. The indication of the recent work is that, with the present system, care taken in the actual technique of drilling, trimming, and setting the strands in the holder can significantly decrease the scatter, and that with such care in technique the data can be expected to give approximately 2 percent standard deviation, which is accounted for by identifiable random errors.

It is believed that this degree of accuracy is adequate for the purposes of this research. There remain the questions of how to interpret the above-mentioned diameter effect, the edge-versus-center strand effect, and the overall question of comparison with motor burning rate data.

C. Measurement of Burning Rates in a Radial Burning Grain

Firing tests were performed with hollow tubular propellant grains in a small laboratory type rocket motor, in order to test the validity of strand burner data. Divergent reports from other laboratories on this question indicated the need for close examination of this point.

The firings were made with ammonium perchlorate, P-13 resin, propellant in a radial burning motor (Fig. 5). The radial design, instead of an end-burning design, was chosen for two reasons: (1) With a single firing, it is possible to determine a complete $r - p$ curve over a reasonably wide range; (2) With charges limited to about 1.4 lb., the capacity of the laboratory mixer, an end-burning design would require nozzles of very small aperture susceptible to plugging by ash during firing.

A typical pressure-time trace is shown in Fig. 6. To determine the burning area at any moment, it is necessary to integrate the curve up to that moment to measure the mass that has burned. To determine the burning rate, after the area has been determined, it is merely necessary to note the instantaneous pressure and use the theoretical $p - k$ relation given in Ref. 5.

Burning rate $r - p$ curves determined in this manner are shown in Fig. 7, in comparison with strand-burner measurements with 1/4 inch round strands. The mystery that is still not explained is why the motor rates are <u>less</u> by about 7% than the strand rates. Possible sources of difference between motor rates and strand rates are the following:

1. Small diameter strands tend to burn a few percent (about 3%) more slowly than larger diameter strands (See Section B). But this is in the wrong direction to explain our discrepancy.

2. Strands made by the wax-mold process burn more rapidly, about 7%, than

strands cut from the interior of a large grain (See Section B). This is in the right direction.

3. Heat loss by outward radiation from the active flame zone, which affects a strand but not a hollow-grain charge, would produce a calculated lower strand rate by about 4% (See Section E).

4. Heat return to the burning surface from the hot product gases in the center cavity of a hollow grain charge, based on the experimentally measured gas emissive power reported in Section E, would raise the motor burning rate by about 2%. The latter two radiation effects produce a differential of about 6%, at 500 psi, but in the wrong direction.

The net effect of the four factors thus considered is to predict that 1/4 inch strands made by the wax mold process ought to burn about 3% more slowly than radial motor charges, for P-13 propellant, 80:20 mixture, at 500 psi. The observed discrepancy is about 7% in the opposite direction. No explanation is known for this mystery, but a closer experimental study of motor firings is indicated.

D. The Study of Particle Size Effects on Burning Rates

Empirically, it is well-known that the finer the oxidizer grind, the greater the burning rate. In the research described in Ref. 1, it was shown that this effect of particle size is more pronounced at high pressures than at low pressures, in general agreement with observations. The theory explains this by saying that the pure chemical reaction rate is rate-controlling at low pressures, while gaseous diffusion is rate-controlling at high pressure. (See Eq. 1 for the relative importance of the first and second terms.)

The effect of particle size is contained in the $\underline{b}$ parameter theoretically in the factor μ, the mass content of each fuel pocket. An estimate by Eq. (3) of the value of μ that is needed to produce the experimentally observed $\underline{b}$ for a typical medium grind propellant leads to a mass that would be equivalent to about a 5 micron cube of fuel resin. It is, therefore, suggestive to identify the average fuel vapor pocket with the average cavity in the solid phase between adjacent perchlorate particles. The mechanism that is visualized is that each such resin pocket (average size 5 microns) is rapidly vaporized when it emerges to the burning surface, forming a vapor pocket in the flame zone.

To verify this hypothesis, and to determine empirically the connection between particle distribution and the $\underline{b}$ parameter, tests are planned on propellants of well-defined particle size. Two requirements present themselves: (1) to be able to measure particle size distributions; and (2) to be able to separate ground oxidizer in reasonable quantities into prescribed particle size ranges, i.e., the so-called classifying process.

The most common instrument for particle size distribution analysis in the perchlorate industry today is the Sharples Micromerograph, an air column in which a sample of the powder is allowed to settle, the rate of accumulation of weight at the bottom being converted to particle size distribution by application of Stokes' Law. Because of difficulties that have been reported by others with agglomeration of fine particles to appear as coarse particles, and failure to achieve full recovery at the bottom of the sample injected at the top, it was decided to purchase a different kind of apparatus for our laboratory.

The equipment we use is a Mine Safety Appliance Company liquid sedimentation analyzer (Fig. 8 and 9), which works on the same principle as the Micromerograph but, using a liquid, in a lower range of particle Reynolds number. The rate of settling is determined, for the coarse fraction down to about 25 microns in chlorobenzene, by gravity settling. A centrifuge is used to determine the distribution of particles smaller than this. Dispersing and settling liquids that have been found satisfactory are: benzene and chlorobenzene for the diameter range from 1 to 100 microns, and butyl sebacate and ethyl phthalate for the range from 5 to 500 microns. It has been found that this instrument gives results that are more acceptable than the air sedimentation equipment. More tests for comparative purposes are underway (See Ref. 8 for survey of size analysis problem).

The second aspect of the particle size work is separation in quantity from a ground stock of broad distribution. For this purpose, various elutriation schemes were studied, and the air stream elutriator of Fig. 10 was adopted (Ref. 6,7). The performance of the elutriator is illustrated by the measured distributions of Fig. 11. Although not as sharp a separation as originally desired, it is considered adequate as a means for establishing the connection between particle size and the $\underline{b}$ parameter.

E. The Effect of Radiation Upon the Burning Rate of Composite Solid Propellants

The sole mechanism of energy feedback from the reaction zone to the propellant surface that was considered in the granular diffusion flame theory was conduction. In order to account for possible radiation feedback, this theory has been modified by the addition of a small radiation component. The results of this work, referring to Fig. 12 and the following list of symbols are given below. (For comparison see Ref. 9).

I_F = radiant energy feedback from flame

I_L = energy loss radiated from the flame

I_x = energy radiated into the flame zone from external sources (e.g., I_{core} from a hot gas core in a hollow burning grain)

α_F = fraction of I_x absorbed without reaching solid surface

Q_c = enthalpy of combustion = $C_{pg}[T_{f(ad)} - T_o]$

T_f = final temperature of combustion products

$T_{f(ad)}$ = final temperature (adiabatic case)

T_s = temperature of the solid surface

T_o = ambient temperature of propellant

r_o = hypothetical burning rate in absence of radiation

r = actual burning rate (with radiation) = $r_o + \Delta r$

ρ_p = density of solid propellant

C_s = specific heat of solid

Q_s = exothermic heat of solid-to-gas reaction at surface

C_{pg} = specific heat of gaseous products

τ_o = adiabatic time of gaseous reaction in flame

τ = actual time for gaseous reaction

For the general case the solution is:

$$\frac{\Delta r}{r_o} = \frac{\frac{1}{2}[I_F + (1-\alpha_F) I_X]}{r_o \rho_p [C_s(T_s - T_o) - Q_s]} + \frac{\frac{1}{2}[I_X - I_L]}{r_o \rho_p [C_{pg}(T_{1(ad)} - T_s)]} + \frac{1}{2}\left(\frac{\tau_o}{\tau} - 1\right) \quad (4)$$

For the case of a burning strand where

$$I_X = 0 \; ; \; I_L = I_F \; ; \; T_1 < T_{1(ad)} \; ; \; \frac{\tau_o}{\tau} < 1$$

$$\frac{\Delta r}{r_o} = \frac{\frac{1}{2} I_F}{r_o \rho_p [C_s(T_s - T_o) - Q_s]} - \frac{\frac{1}{2} I_F}{r_o \rho_p [C_{pg}(T_{1(ad)} - T_s)]} + \frac{1}{2}\left(\frac{\tau_o}{\tau} - 1\right) \quad (5)$$

For the case of a hollow burning grain where it is assumed that

$$I_X \cong I_{core} + I_L \; ; \; I_L = I_F \; ; \; \alpha << 1 \; ; \; T_1 = T_{1(ad)}$$

and $$\frac{\tau_o}{\tau} = 1$$

$$\frac{\Delta r}{r_o} = \frac{I_F}{r_o \rho_p [C_s(T_s - T_o) - Q_s]} + \frac{\frac{1}{2} I_{core}}{r_o \rho_p} \left\{ \frac{1}{[C_s(T_s - T_o) - Q_s]} + \frac{1}{[C_{pg}(T_{1(ad)} - T_s)]} \right\} \quad (6)$$

Measurements of I_L from flames of strands (80:20 mixture) burning at 500 psi (Fig. 13, 14) came out to be 6.4 cal/cm^2 sec. This corresponds to a flame emissivity of 0.075 based on a theoretical flame temperature of 2800K. Equating I_F to I_L, the evaluation of $\Delta r/r_o$ for strands from Eq. (5) leads to:

$$\frac{\Delta r}{r_o} = .020 - .006 + 1/2(.93 - 1) = -.021$$

Measurements of I_{core} from the cavity of the test motor (Fig. 15) at 500 psi came out to be 2.4 cal/cm^2 sec. This corresponds to a gas emissivity of 0.029 based on the same temperature. (The evaluation of I_{core} from the flux

measurement in Fig. 15 involves an integration over the hemisphere of gas adjacent to the element of solid surface and takes into account Lambert's cosine law.) This emissive power, incidentally, is about one-fourth of the value computed for the calculated equilibrium gas mixture at the estimated gas temperature, using the charts of Ref. 10, 11. No firm explanation can be given for this, but the discrepancy could be due to the very imperfect knowledge of pure gas emissivities. The burning rate correction in this situation, from Eq. (6) is:

$$\frac{\Delta r}{r_o} = .040 + (.0075 + .0015) = + .049$$

Consequently, the burning rate in a hollow motor can be expected to exceed that of a strand by about 7%. This is apart from erosive effects, strand diameter effects, etc.

The radiation intensity is greater as the oxidizer particle size is increased, with this effect most pronounced at lower pressures and disappearing as the pressure increases. Experiments have shown a small effect of strand diameter on the radiation intensity, with the larger diameters giving higher intensities. Also, tests with a receiver picking up the radiation from the side as the flame burned past have shown that the radiating zone of the flame is quite thin and close to the solid surface, as is assumed in the above theory and in Fig. 12.

The work to date indicates that radiation is a minor mode of energy transfer in the propellant studied, so that the basic assumption of Eq. (1) is justified. However, it may still cause significant increases in the burning rates of hollow charges over strands.

The fact that this is not borne out by experiments, as explained in Section B, is still an unsolved mystery.

F. Conclusion

As a partial statement of progress on clarification of the factors that affect the steady-state burning of solid propellants, the following results can be reported:

1. The magnitude of radiant energy transfer in ammonium perchlorate - P-13 type composite propellants is sufficiently small to justify the pure conduction mechanism underlying the theoretical burning rate law, Eq. (1).

2. There are substantial differences between the burning rates in hollow charge motors and ordinary strands that are not explainable by known mechanisms. This requires further research.

3. The liquid sedimentation particle size analyzer appears to perform as well as the micromerograph, and an air stream elutriator appears satisfactory for particle separation in bulk amounts in the range from 100 microns down. This will enable research on particle size effects to proceed.

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LEGEND OF ILLUSTRATIONS

FIGURE	TITLE
1	Schematic drawing of purged strand burner showing typical one-quarter inch diameter strand in one inch I.D. chimney. Flow velocity of nitrogen purge gas is usually about 2 ft/sec in chimney. Included is rapid water injection system for quenching strands during burning to allow inspection of burning surface.
2	Photograph of wax molds, side and front views, and some strands as removed from molds. At curing temperature of 185°F wax is soft and strands are easily cut out from molds.

FIGURE	TITLE
3	Photograph of strand in strand burner with one half of chimney removed. Longitudinal chimney joint to right is insulated with tape while joint to left is bare. Ignition and fuse wires are thereby insulated to the right of the strand and grounded to the left.
4	Close-up of strands quenched during burning. First two on left burned at 165 psig while two on right burned at 500 psig. Only the strand on the extreme right did not have a coating of inhibitor. Tilted surfaces are shown on outside strands while dished surfaces to be expected from ignition along a cylinder are shown in center strands. Strands had burned about 2 inches before quenching. Only the uninhibited case at the right is considered unacceptable.
5	Schematic cut-away drawing of radial burning motor.
6	Typical pressure-time trace of radial burning motor. This trace illustrates typical sources of error such as ignition transient through which trace must be extrapolated for computing instantaneous burning surface radius, and the relatively round cut-off at end of run.
7	Burning rate vs pressure curves from motor firings and from strand burner. Generally higher strand rate, with maximum discrepancy at lower pressures, is clearly shown.
8	Photograph of MSA particle size analyzer showing from left, high speed centrifuge, sediment column viewer and tapper, electric timer, and low speed centrifuge, with magnetic voltage regulator shown to rear of viewer. Note image of sedimentation tube and sediment column in viewer.
9	Photograph of sedimentation tube showing sediment column. Sample injector shown to right.
10	Schematic drawing of two-stage elutriator. Distribution of fractions among the collecting vessels is coarse, medium, and fine, from left to right.
11	Size distribution of fractions separated by elutriator. Separation of fines from coarses is not sharp, but acceptable for initial studies.
12	Solid propellant energy flux diagram including effect of radiant energy added in addition to that originating in flame zone.
13	Schematic diagram of strand burner equipped for radiation measurement, showing 0.25 inch diameter strand mounted in 1.25 inch diameter chimney, and purged with 10% O_2 plus 90% N_2. Cross-section of window holder shows radiation screens and window purge assembly, through which radiation is fed to a blackened vacuum thermocouple.

FIGURE	TITLE
14	Typical oscillograph traces of radiation thermocouple output. First bright dot which is seen to left on base line occurs at ignition while succeeding three occur when fuse wires are burned. Known position of fuse wires in bomb gives position of flame at any time relative to radiation receiver. Decrease in signal as burning proceeds corresponds to increasing distance of flame zone from receiver.
15	Schematic diagram of radial burning motor showing collimating apertures and radiation receiver which sees only rays passing through nozzle. Radiation receiver is a blackened vacuum thermocouple.

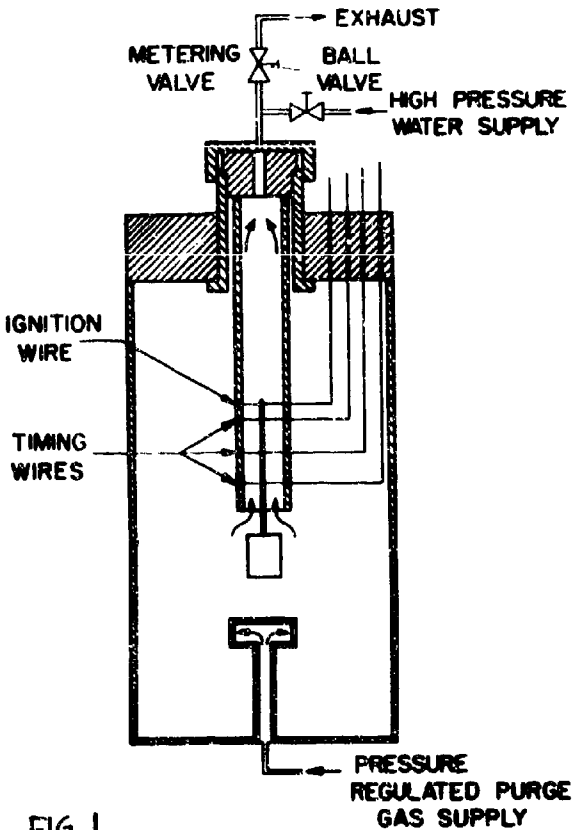

FIG. 1 PURGED STRAND BURNER

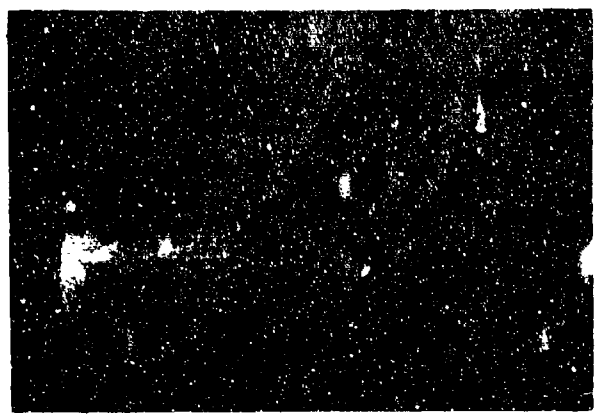

FIG. 2 WAX MOLDS AND STRANDS

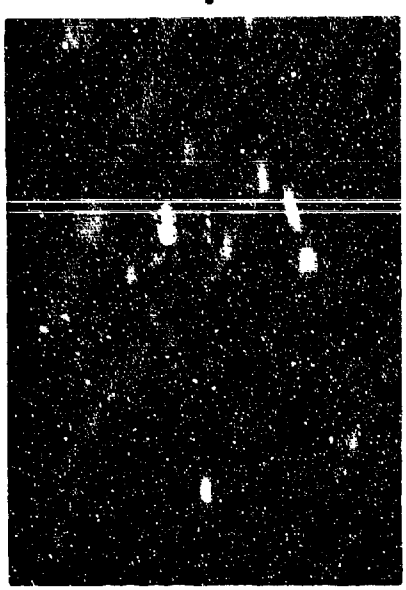

FIG. 3 STRAND HOLDER AND MOUNTED STRAND

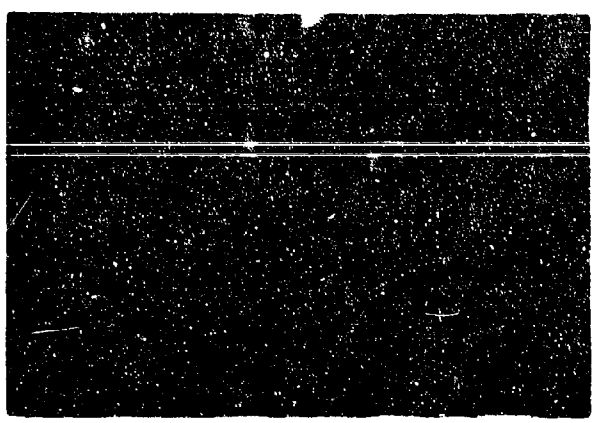

FIG 4
QUENCHED ONE-QUARTER INCH DIAMETER STRANDS OF 80:20 AP + PI3 PROPELLANT. BURNING PRESSURES FROM LEFT ARE 165, 165, 500, AND 500 PSIG. FIRST THREE STRANDS ARE INHIBITED AT SURFACE, FOURTH IS NOT. (1060)

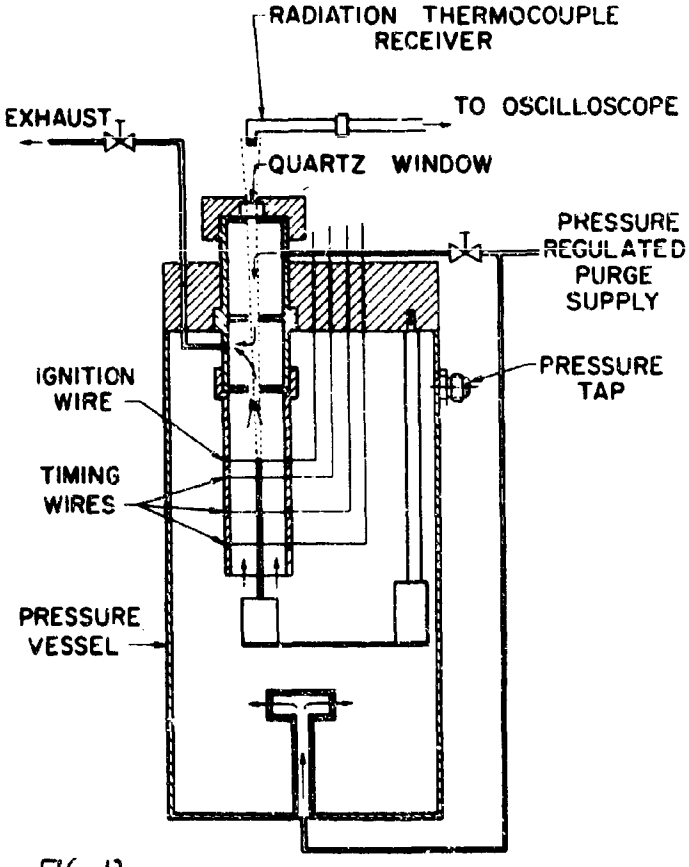

FIG 13
STRAND BURNER FOR RADIATION MEASUREMENT

RADIATION SIGNAL TRACES

RP-2 RADIATION THERMOCOUPLE
80:20 AMMONIUM PERCHLORATE - P13 PROPELLANT
ONE QUARTER INCH DIAMETER STRANDS
IN ATMOSPHERE OF 10% O_2
WITH 90% N_2
RP-2 CALIBRATION FACTOR=0.0265 $\frac{\mu VOLTS}{\frac{CAL}{CM^2\ SEC}}$

PRESS. 100 PSIG
PREAMP GAIN 300
FILTER ATTENUATION 1.3
SCOPE SENSITIVITY 10 MV/CM
SWEEP RATE 5 SEC/CM
FUSE WIRE SPACING 1 INCH
$q_{R/A}$ = 10.38 $\frac{CAL/SEC}{CM^2}$
u = 0.299 $\frac{CM}{SEC}$
$q_{T/A}$ = 85.2 $\frac{CAL/SEC}{CM^2}$
q_R/q_T = 0.122
ϵ = 0.123

PRESS. 400 PSIG
PREAMP GAIN = 300
FILTER ATTENUATION 1.3
SCOPE SENSITIVITY 10 MV/CM
SWEEP RATE 2 SEC/CM
FUSE WIRE SPACING = 1 INCH
$q_{R/A}$ = 6.30 $\frac{CAL/SEC}{CM^2}$
u = 0.529 $\frac{CM}{SEC}$
$q_{T/A}$ = 151 $\frac{CAL/SEC}{CM^2}$
q_R/q_T = 0.0417
ϵ = 0.0769

FIG. 14.

SCHEMATIC OF RADIAL BURNING MOTOR WITH RADIATION RECEIVER

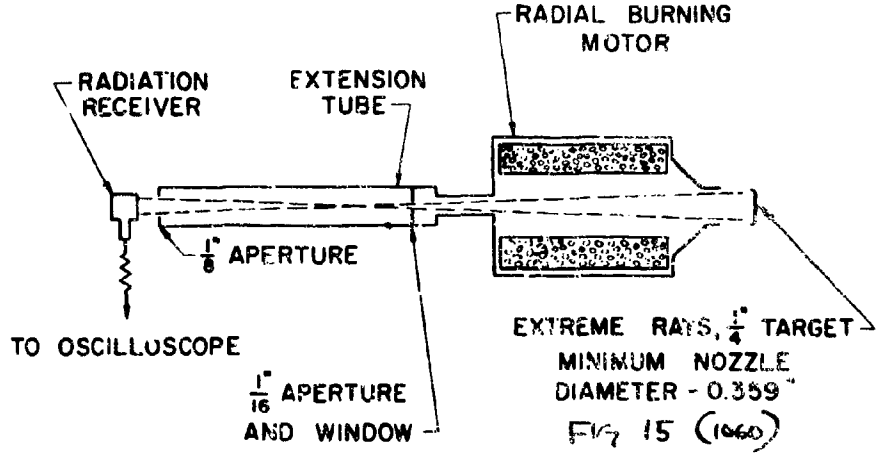

FIG 15 (1960)

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